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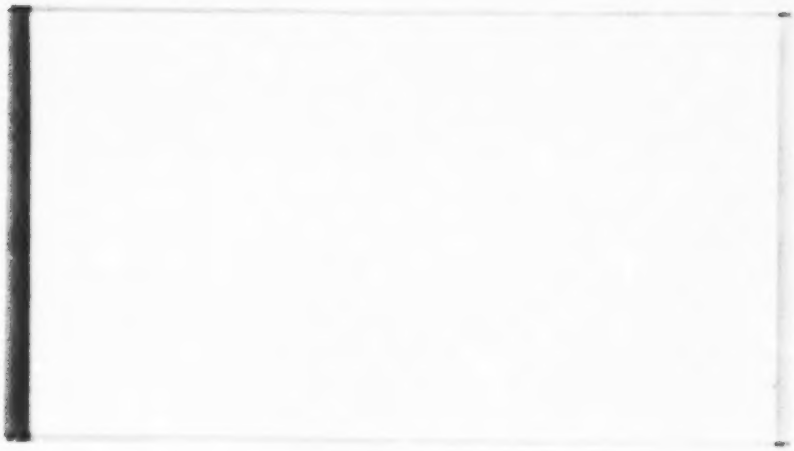

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A STUDY ON HYDRIDE BLISTER FORMATION IN BRUCE 3 AND 4 AND PICKERING 5 AND 6

Report No 86-153-K

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Cross Currents Research &
Policy Consulting Limited

ABSTRACT

For this study a computer code was developed to estimate quantitatively the number of pressure tubes containing hydrides blisters in reactors Bruce 3 and 4 and Pickering 5 and 6 as a function of time. It uses the best information available at this time on the variables which affect the formation of hydride blisters: initial hydrogen content; hydrogen pick-up rates; the hydrogen threshold value for blister formation; and the location of the four garter springs. The inputs in the program are random variables; this allows for uncertainties in parameters.

Based on the most likely scenario and the best information, it is estimated that Bruce 3 contains, at the present, one or two blistered pressure tubes. This will increase to about seventeen in twelve more years. It was also found that Pickering 5 and 6 will have more blistered tubes than Bruce 3 and 4 for the same years of operation. Finally, it was observed that the most important source of uncertainty was the distribution function of the hydrogen threshold value.

job	file	date	report no.
740684-536-051	823.21	November 28, 1986	86-153-K

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EXECUTIVE SUMMARY

A STUDY ON HYDRIDE BLISTER FORMATION IN BRUCE 3 AND 4 AND PICKERING 5 AND 6

M. Leger and D.V. Leemans

A computer code was developed to estimate the probabilities of hydride blister formation in Bruce 3 and 4, and Pickering 5 and 6 reactors as a function of time. The purpose of the study was twofold: to provide estimates of the number of blistered tubes based on the best information available; and to investigate quantitatively the dependence of the blistering phenomenon on the informational inputs. These random variable inputs were: initial hydrogen content, hydrogen pick-up rate; hydrogen threshold value for blister formation; and the location of the four garter springs.

Based on the most likely scenario and the best information, it is estimated that Bruce 3 contains at the present one or two blistered pressure tubes; in twelve more years (after twenty reactor years) it will have seventeen pressure tubes with blisters. Not all the blistered tubes will be in the central core of the reactor; the outer zones are not immune to blister formation. Pickering 5 and 6 will have more blistered pressure tubes than Bruce 3 and 4 for the same number of reactor years.

The dependence of the results on initial hydrogen content, hydrogen threshold distribution and garter spring locations was studied. It was shown that the biggest dependency was on hydrogen threshold distribution; garter spring location and initial hydrogen content affect the results much less.

The method used to develop these estimates can be extended in two ways. It can be applied to reactors with two garter springs. Furthermore, it is recommended that the computer code be extended to include, blister growth, cracking and finally pressure tube failure.

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TABLE OF CONTENTS

		PAGE
1.0	INTRODUCTION	1
2.0	THE THEORY	2
3.0	THE DEVELOPMENT OF INPUTS	2
4.0	EXPERIMENTAL RESULTS	3
4.1	Introduction	3
4.2	Bruce 3 Results	3
4.3	Other Reactors	4
4.4	Dependence of the Results on the Choice of Parameters	4
5.0	DISCUSSION	5
6.0	CONCLUSIONS	6
7.0	RECOMMENDATIONS	7
REFERENCES		8
APPENDIX 1 - HYDROGEN THRESHOLD		17
APPENDIX 2 - INITIAL HYDROGEN CONTENT		20
APPENDIX 3 - PICK-UP RATE OF HYDROGEN		22
APPENDIX 4 - RELATIONSHIP BETWEEN SPAN LENGTH AND TIME TO CONTACT		23
APPENDIX 5 - GARTER SPRING LOCATIONS		26
DISTRIBUTION		Last Page

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TO: Dr. D. Mills
Director of Research

A STUDY ON HYDRIDE BLISTER FORMATION IN BRUCE 3 & 4 AND PICKERING 5 & 6

M. Leger and D.V. Leemans

1.0 INTRODUCTION

The failure of the Zircaloy pressure tube in Pickering Unit 2 in 1983 resulted from the formation of hydride blisters on the outside surface of the pressure tube where it contacted its surrounding calandria tube. Since that time attention has been focused on the behaviour of Zr 2.5wt% Nb pressure tubes in contact with calandria tubes. A comprehensive research program, TRAC (Tube Response After Contact), has been producing results relevant to the evaluation of such a situation. A recent assessment of the need to implement SLAR (Spacer Location and Repositioning) incorporated some of the major findings of the TRAC program/1/. A major recommendation of this report was to implement SLAR on the four units where such implementation can be expected to significantly increase the life of the unit. The four units were B3, B4, P5 and P6. In order to significantly improve on this assessment, it is necessary to provide a time dependent, quantitative evaluation of the numbers of tubes likely to have blisters in these reactors. The work reported here, which was OHRD originated and encouraged by the SLAR assessment group, uses a recently developed computer program to calculate the probabilities of blister formation in each of these units/2/. This type of simulation study has two main purposes.

1. Making numerical estimates based on best available information;

2. Establish the dependencies of blister formation on a variety of parameters whose importance can then be assessed.

Both of these activities are important. The first one is a useful input in economic cost calculations. The second one can be used in determining which information is crucial and therefore can help in establishing research priorities.

The report sketches the theoretical background used in the simulation, shows the development of the input distributions, gives the results of the computer experiments and a discussion of their meaning.

86-153

2.0 THE THEORY

The model used in the computer simulations is the mathematical expression of the work done in the TRAC program. Its assumptions are:

- The pressure tube can be divided into (n+1) areas, n being the number of garter springs.
- For each area the probability of blister formation is the product of the probability of pressure tube/calandria tube contact AND the probability of the hydrogen content exceeding a critical threshold.[1]
- The probability of pressure tube calandria tube contact is only a function of the span length, the area of the pressure tube (inlet, outlet and inner), the location of the pressure tube in the reactor (central, intermediate and outer zones), the type of reactor and time. The contact time is also a random variable.
- The critical hydrogen threshold is allowed to vary over the areas within the pressure tube, as well as with the zones. However, it is not a function of time.
- The pick-up of hydrogen is assumed to be proportional to time;
- The probability of a blister in a pressure tube is the OR combination of the probabilities of a blister in each area.

All the input variables are considered to be random; their probability density distributions can take two forms: Normal and Weibull. The resulting output is the cumulative probability and the probability density for blister formation as a function of time.

3.0 THE DEVELOPMENT OF INPUTS

The flexibility of the program brings with it the responsibility for the user to obtain the best data inputs related to the specific reactor. This considerable task is described in separate appendices in detail.

The following inputs are required:

- The threshold hydrogen content. If the hydrogen concentration in the pressure tube exceeds this value and there is contact with the calandria tube then a hydride blister will form. Four possible scenarios were established and scenario 3.0 is judged the most likely at the present. The details on the determination of these threshold values are given in Appendix 1.
- The initial hydrogen content. The distributions used are derived in Appendix 2.

---

1. The AND and OR vocabulary is widely used in fault-tree analysis. AND indicates that all the conditions have to be fulfilled to have a successful outcome; the probabilities are multiplied if the conditions are uncorrelated. OR indicates that it is sufficient for a successful outcome that one of the conditions be fulfilled.

- The hydrogen pick-up rate. The treatment of the scarce data is discussed in Appendix 3.

- The relationship between span length and time to contact. This necessary simplification allowed the carrying out of extensive Monte Carlo simulations which would not be possible if CDEPTH or TUBESAG were to be used. The development of these relationships is given in Appendix 4.

- Garter spring locations. Some assumptions had to be made on the positions of the garter springs since no data on Bruce 3 and 4 and Pickering 5 and 6 garter springs were available. The use of the measurements made for Bruce 6 and Pickering 7 is explained in Appendix 5.

4.0 EXPERIMENTAL RESULTS

4.1 Introduction

It is neither possible nor useful to present all the results obtained. The data for Bruce 3 with Scenario 3.0 (the most likely scenario) will be presented in detail. The reason for the choice of Bruce 3 is that, of the four reactors considered, it is the most likely to have blisters now. A summary of the results for other reactors will follow. Lastly the dependence of the results on the characteristics of the distributions will end this section. All the results will be further examined in the discussion part.

4.2 Bruce 3 Results

The most plausible scenario for Bruce 3 at the present is based on the following inputs:

- the threshold hydrogen is the one derived in scenario 3.0 of Appendix 1.

- the initial hydrogen concentration is the Weibull distribution based on the hydrogen measurements of the first and last tube of each ingot;

- the pick-up rate is the same for all runs and is the Weibull distribution based on the nine observation points mentioned in Appendix 3;

- the time to contact as a function of span length is based on work done on Bruce 6 data as described in Appendix 4;

- the garter spring locations are the ones measured for Bruce 6. No distributions were used, just the plain data set.

The results are shown in Figures 1-4. Figure 1 shows the relative probabilities for blister formation in the different zones of the reactor. It indicates that for this situation a tube in the outer zone has a higher probability of hydride blister formation than a tube in the central core. The expected number of tubes with blisters as a function of time is shown in Figure 2. It shows that after 20 years of operations about seventeen tubes (out of a total of 480) are expected to have blisters. Figure 3 shows the specific probability density distributions after 8, 10, 12 and 14 years, while Figure 4 displays the function 1-F(X) [F(X) is the cumulative probability) as a function of the number of tubes with blisters. This last figure is useful in that it indicates the probability of

having more than X tubes with blisters. As an example, it shows that after eight reactor years -- which is now -- there is about a 20% chance that there are more than two tubes with blisters in the reactor.

4.3 Other Reactors

The most probable scenario was also calculated for Bruce 4, Pickering 5 and Pickering 6. The inputs used can be summarized as follows:

- Scenario 3.0 is still used as the basis for hydrogen threshold;
- The initial hydrogen contents are Weibull distributions. For Pickering 5 and 6 the same distribution is used for the different zones.
- The hydrogen pick-up rate is the same for all reactors.
- The functional relationships between time to contact and span length are slightly different for the Bruce and the Pickering reactors.
- The garter spring locations used were the Bruce 6 database for Bruce 4 and the Pickering 7 database for Pickering 5 and 6 simulations.

Figure 5 displays the expected number of blistered tubes for those three reactors as a function of reactor time. It shows that Pickering reactors are more susceptible than Bruce reactors to hydride blister formation. The reasons for this behaviour will be explained in the discussion.

4.4 Dependence of the Results on the Choice of Parameters

Using Scenario 3.0 for Bruce 3 as the reference set of results, a study was performed of the dependence of the results on the choice of the parameters used to described the relevant input distributions.

There are a large number of interactions that could be studied. In this report only a limited number of interactions will be discussed. The first one, which is considered of primordial importance, is the role of the threshold hydrogen content. Four scenarios were studied for Bruce 3 (other parameters were held constant) and the results are shown in Figure 6. This graph shows that roughly doubling the hydrogen threshold value reduces the expected number of blistered tubes by a factor of one hundred, demonstrating the great importance of the hydrogen threshold.

Also the standard deviation of the threshold hydrogen distribution affects severely the results. By reducing the standard deviation by a factor of two the expected number of blistered tubes reduces by a factor of roughly two as shown in Figure 7. The effect of initial hydrogen content was tested by comparing the results for Bruce 3 and Bruce 4 (Figure 8). These three dependencies indicate the sensitivity of the predictions to variations in hydrogen related inputs.

Another largely unknown input is the position of the garter springs. To study the sensitivity of the results to this input, three runs were performed for Bruce 3 with different garter spring

distributions, using the Pickering 7 data set, the Bruce 6 data set and normal distributions based on the observations of the Bruce 6 data set. The results shown in Figure 9 indicate that a factor of two might well be expected because of the uncertainty in the garter spring locations.

5.0 DISCUSSION

Making predictions on the number of blistered tubes in the reactors under consideration is fraught with great difficulties because of the large uncertainties in the inputs. The predictions in this report are only optimal in that they are based on the best formulation of our present knowledge.

The set of figures (Figs. 1-4) describing the most probable scenario for Bruce 3 is informative. It indicates that it is not acceptable to focus only on the central core of the reactor. As Figure 1 shows the probability for a hydride blister is higher in a tube at the outer zone than in the central core. This is partially offset by the large number of tubes in the central core (280 tubes) compared to the outer zone (56 tubes). The reason for this high probability of blisters in the outer zone is that the garter springs are much more out of position (their standard deviation is about four times the standard deviation in the central core). This observation about garter spring positions is well-known and attributed to the impacting of workers during construction.

Figure 2 shows the dramatic increase of the expected number of blistered tubes with time. After about eight years the increase can be approximated with an exponential. Figure 3 gives the shift in the probability density as a function of four reactor operating times. It shows also clearly that the uncertainty increases with time (the distribution spreads out). Figure 4 helps in the evaluation of the question: What is the probability that there are more than X blistered tubes in the reactor?

On the basis of these results a delay of two years in a SLAR operation (from 1987 to 1989) will for Bruce 3 result in an increase of one or two blistered tubes.

The results for the other reactors shown in Figure 5 are interesting for the contrast between Pickering and Bruce reactors. It indicates that even with one hundred tubes less per reactor, the Pickering units will have more blistered tubes for the same years of operations. This can be explained by examining the position of the garter springs in the central core for Pickering 7 and Bruce 6, revealing that the standard deviation for the Pickering case is at least twice that of the Bruce data set. The reasons for this difference are not well understood, but the relative size of the Pickering reactor might be a contributing factor. As the Pickering reactors are younger than those at Bruce, the number of blistered tubes present at this time in Bruce reactors is greater than the number in Pickering reactors.

Figure 6 shows the large dependence of the results on the values of the thresholds chosen. This is a significant finding as the uncertainty in the threshold value is large. This is because of the uncertainty in the tube topology, in the morphology of the contact and in the assumptions made on the heat transfer coefficients. Also the effect of the standard deviation of the threshold distribution shown in Figure 7 is sizeable but less dramatic than the dependence of the results on the average threshold value. The dependence on this standard deviation can be understood by realizing that the mean of the hydrogen content distribution hardly ever reaches 50% of the cumulative threshold distribution within the twenty operating years considered; therefore, the tails of the distribution are important.

The importance of the garter spring location information is well demonstrated in Figure 9. The difference between using the Pickering data set and the Bruce data set has been alluded to above in explaining the difference between Bruce 4 and Pickering 5 and 6 results. The difference between the use of the Bruce 6 data set and the distribution based on this data set is small up to ten reactor years but diverges after that. This difference can be explained by pointing out that the garter spring locations are assumed to be uncorrelated in the distribution simulation; the data sets show this to be incorrect. There is considerable correlation between the motions of adjacent garter springs, expecially for the outer zone garter spring data. A detailed examination shows that the differences between the end results of the two runs (Bruce 6 data set and Bruce 6 distribution) are largest for the outer zone.

In general, these comparisons show that the uncertainty of garter spring location affects the results less than the assumptions made on hydrogen threshold.

6.0 CONCLUSIONS

Based on these simulation studies the following conclusions can be drawn.

1. Of the reactors considered, Bruce 3 is the reactor which now contains the largest number of blistered tubes. It is estimated that it has now one or two blistered tubes which will increase to about seventeen in twelve more operating years.

2. The pressure tubes in the outer zone are also susceptible to hydride blister formation.

3. Pickering reactors will have more blistered tubes than Bruce reactors for the same years of operation.

4. The biggest source of uncertainty is the distribution of the threshold hydrogen. Research to describe accurately this distribution will result in better predictions.

7.0 RECOMMENDATIONS

1. Although it is possible to estimate the probability of blister formation in fuel channels containing four garter springs, it is recommended that the uncertainties of the estimated probabilities be quantified.

2. It is the pressure tube failure probability as a function of time rather than simply blister formation which is of primary interest. It is recommended that the program be extended to allow for the estimation of failure probabilities of pressure tubes.

3. The present capability should be extended to include fuel channels with two garter springs.

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1. Technical Assessment of Spacer Location and Repositioning Nuclear Systems Department, Report No 86066, April 1986.

2. D.V. Leemans, A System Approach to Inspection and Research on Zirconium Pressure Tube After Contact. Cross Currents Research and Policy Consulting Report, December 1985.

BRUCE 3 SCENARIO 3.0

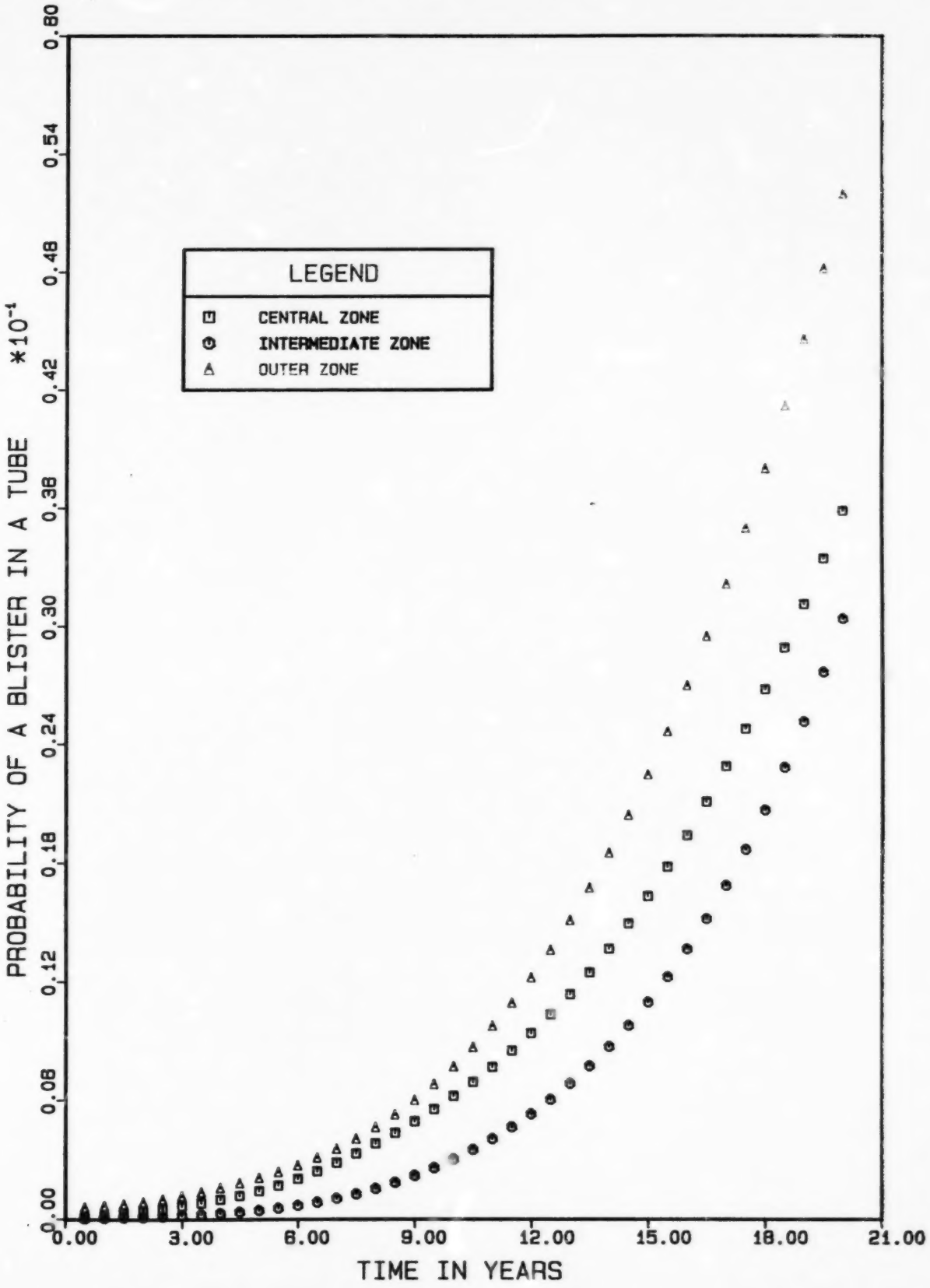

FIGURE 1

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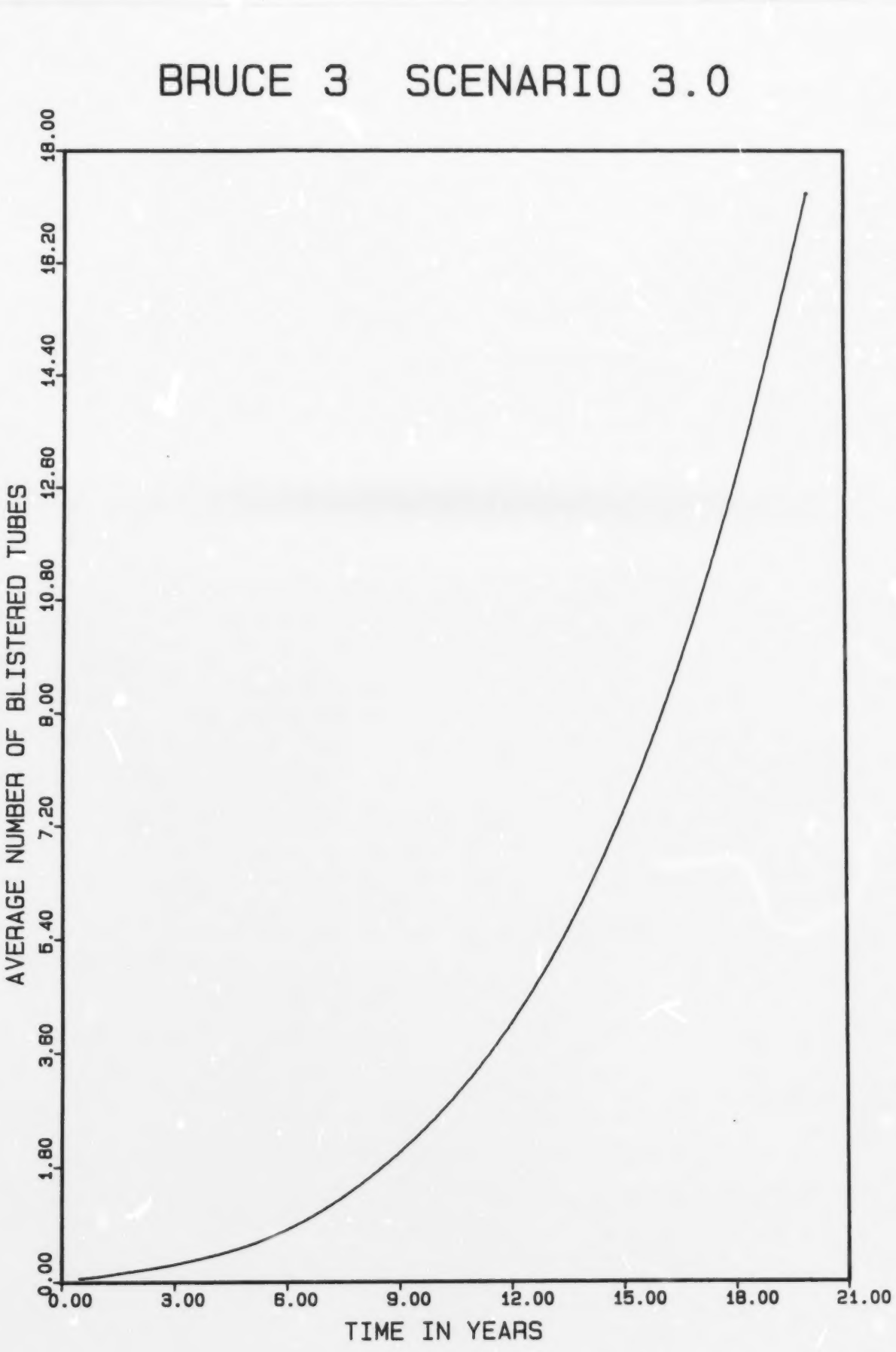

FIGURE 2

86-153

171360 RD

BRUCE 3 SCENARIO 3.0

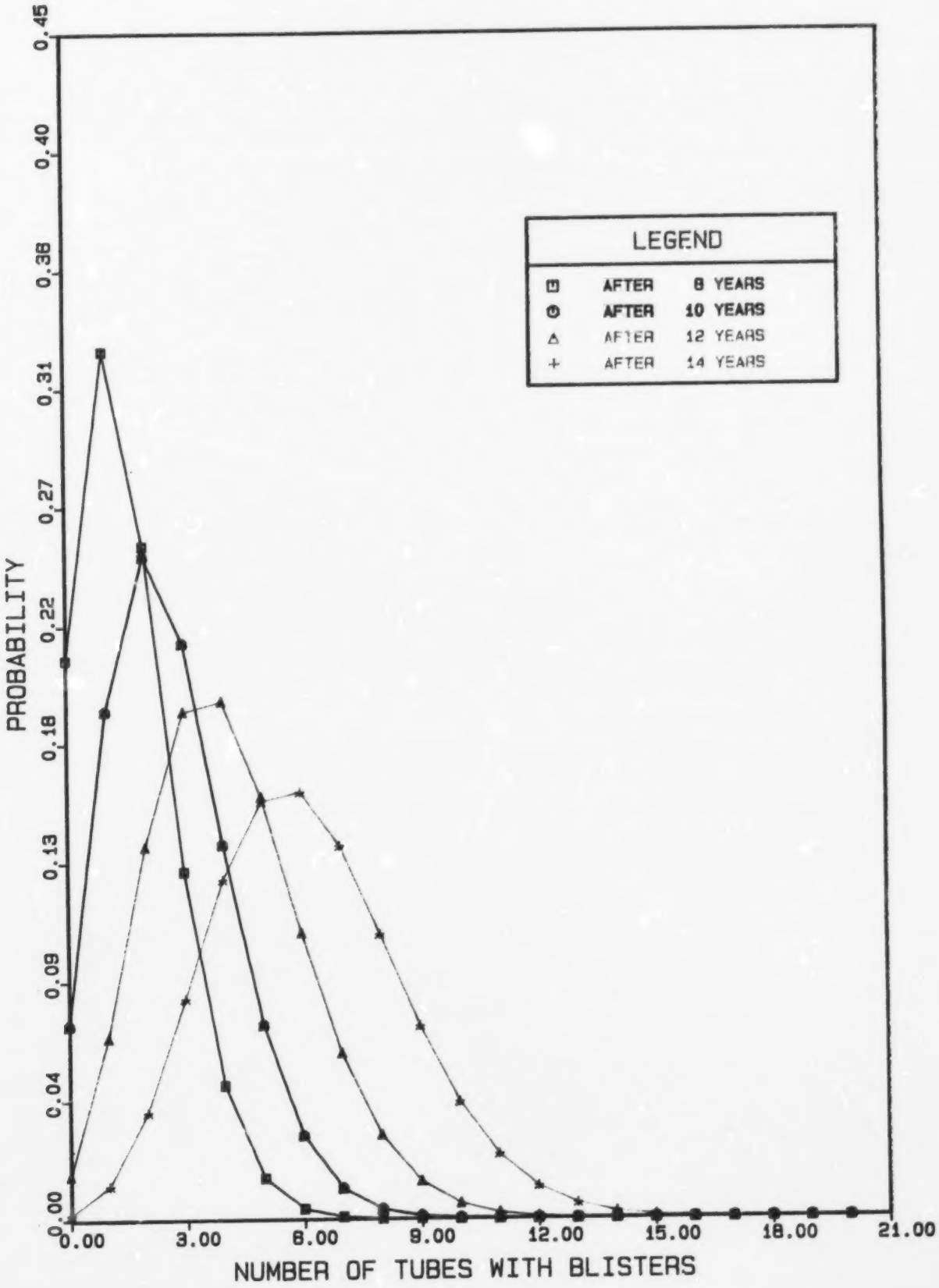

FIGURE 3

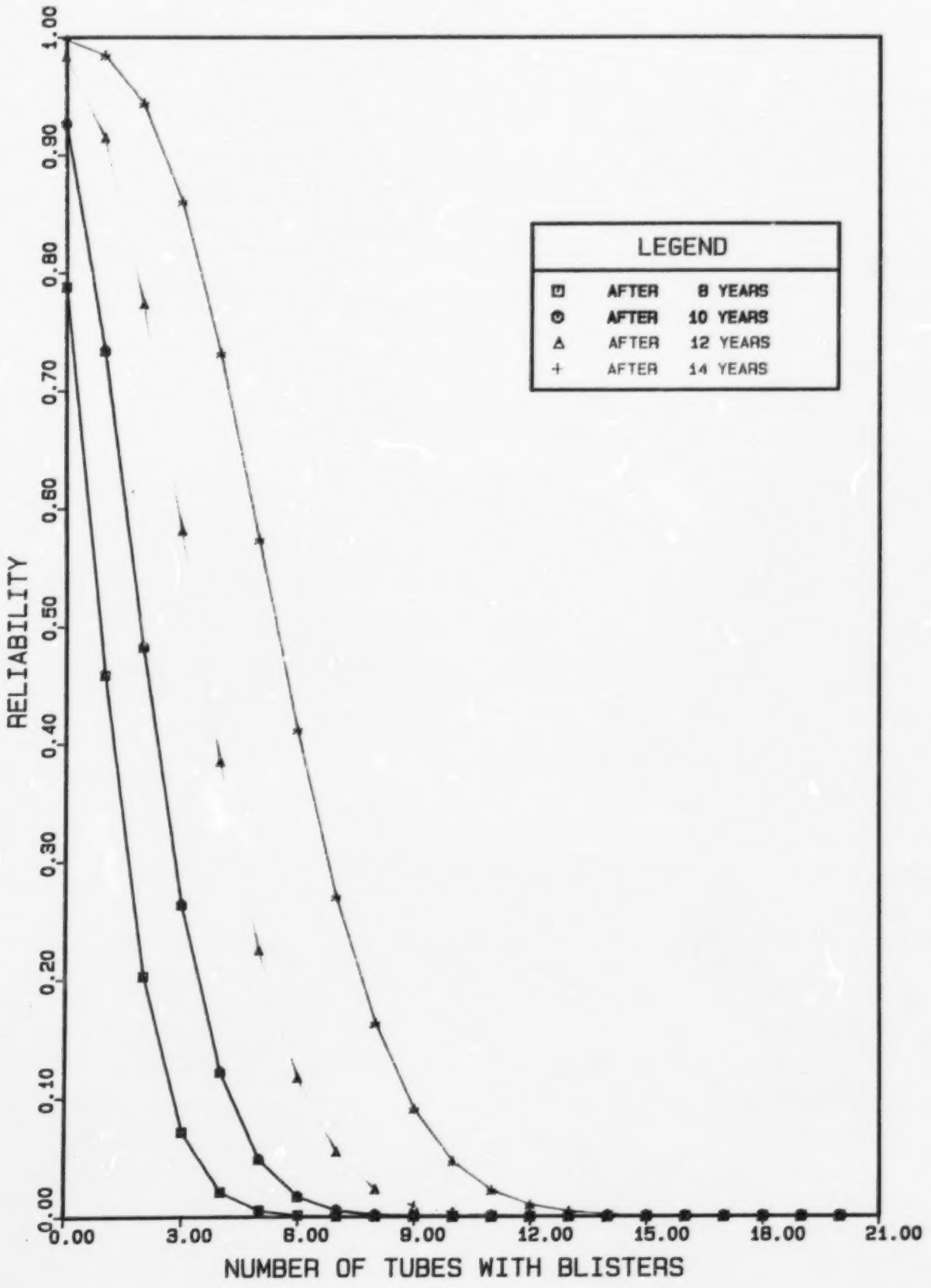
BRUCE 3 SCENARIO 3.0
LEGEND
AFTER 8 YEARS
AFTER 10 YEARS
AFTER 12 YEARS
AFTER 14 YEARS
RELIABILITY
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
0.00
3.00
6.00
9.00
12.00
15.00
18.00
21.00
NUMBER OF TUBES WITH BLISTERS

FIGURE 4

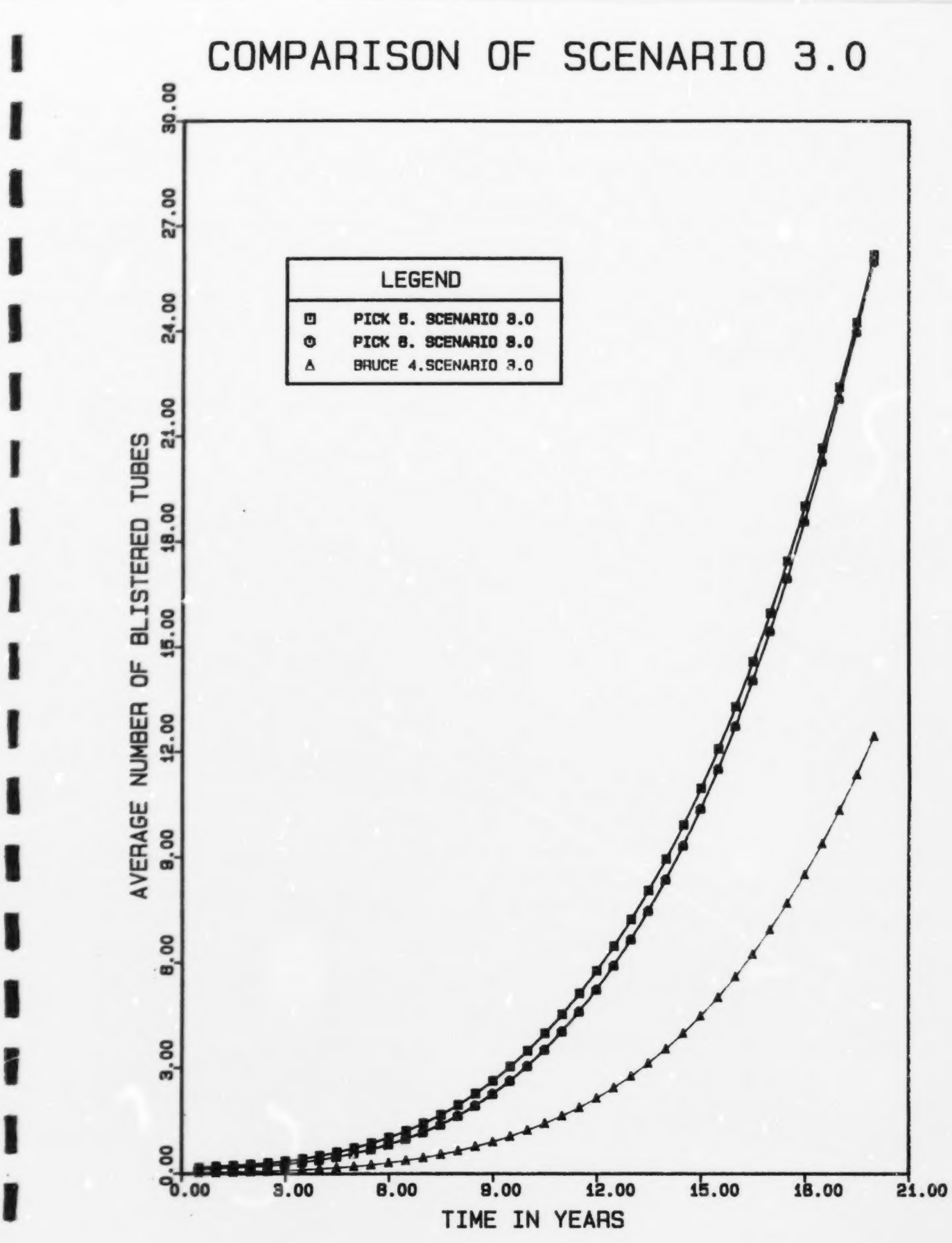
COMPARISON OF SCENARIO 3.0
LEGEND
PICK 5. SCENARIO 3.0
PICK 6. SCENARIO 3.0
BRUCE 4.SCENARIO 3.0
AVERAGE NUMBER OF BLISTERED TUBES
0.00
3.00
6.00
9.00
12.00
15.00
18.00
21.00
24.00
27.00
30.00
TIME IN YEARS
0.00
3.00
6.00
9.00
12.00
15.00
18.00
21.00

FIGURE 5

BRUCE 3. THRESHOLD DEPENDENCE

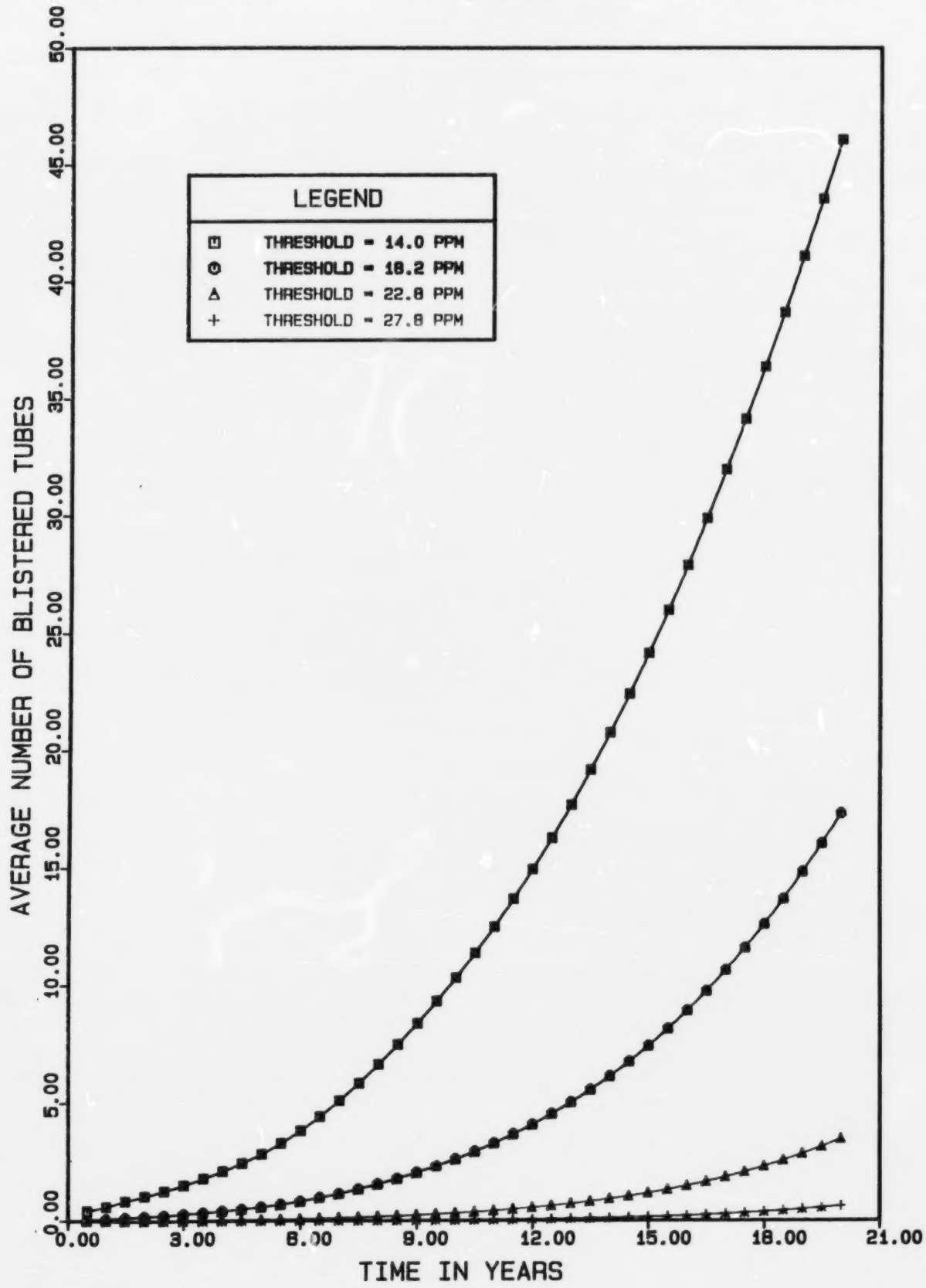

FIGURE 6

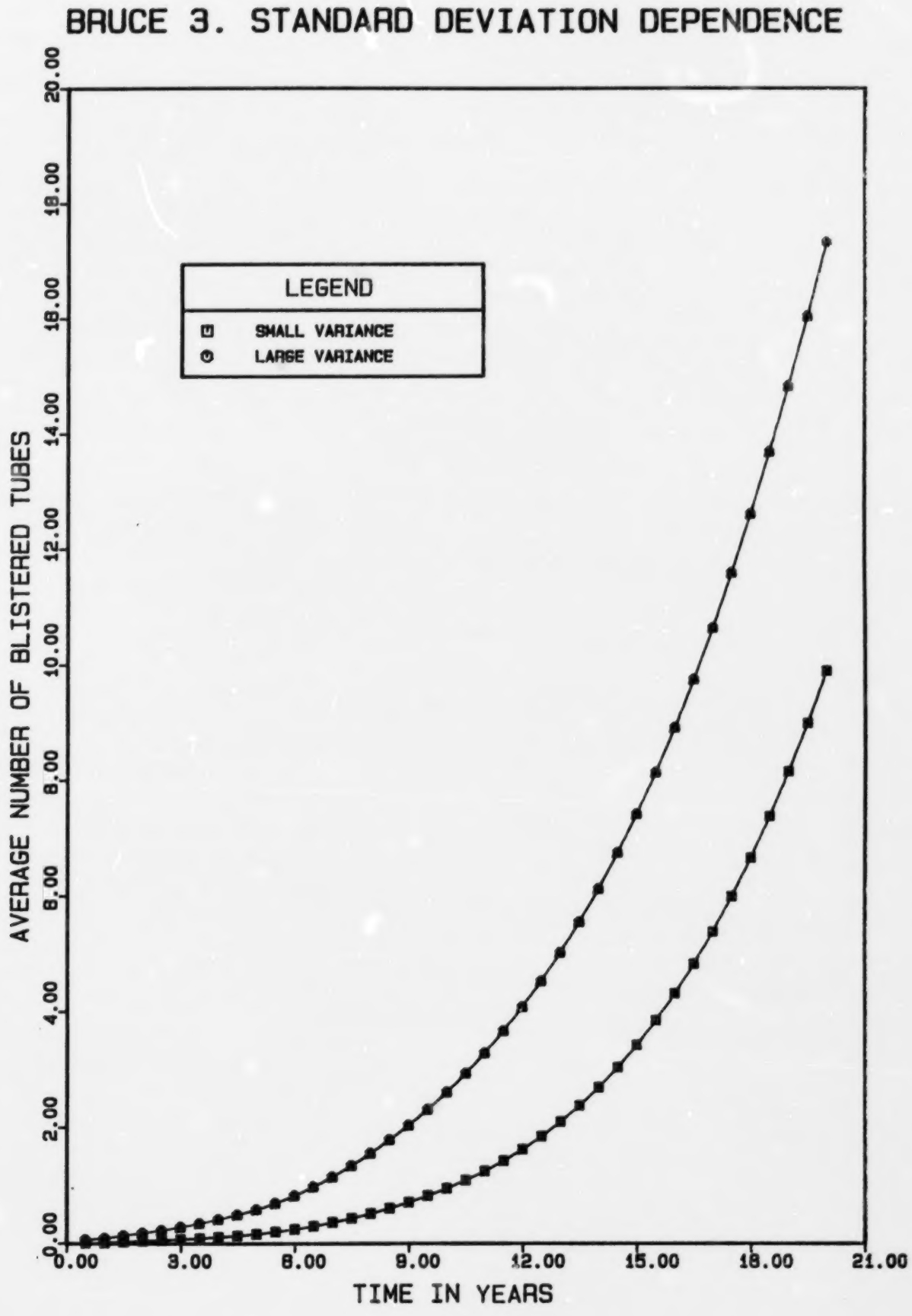
BRUCE 3. STANDARD DEVIATION DEPENDENCE
LEGEND
SMALL VARIANCE
LARGE VARIANCE
AVERAGE NUMBER OF BLISTERED TUBES
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
0.00
3.00
6.00
9.00
12.00
15.00
18.00
21.00
TIME IN YEARS

FIGURE 7

INITIAL HYDROGEN DEPENDENCE

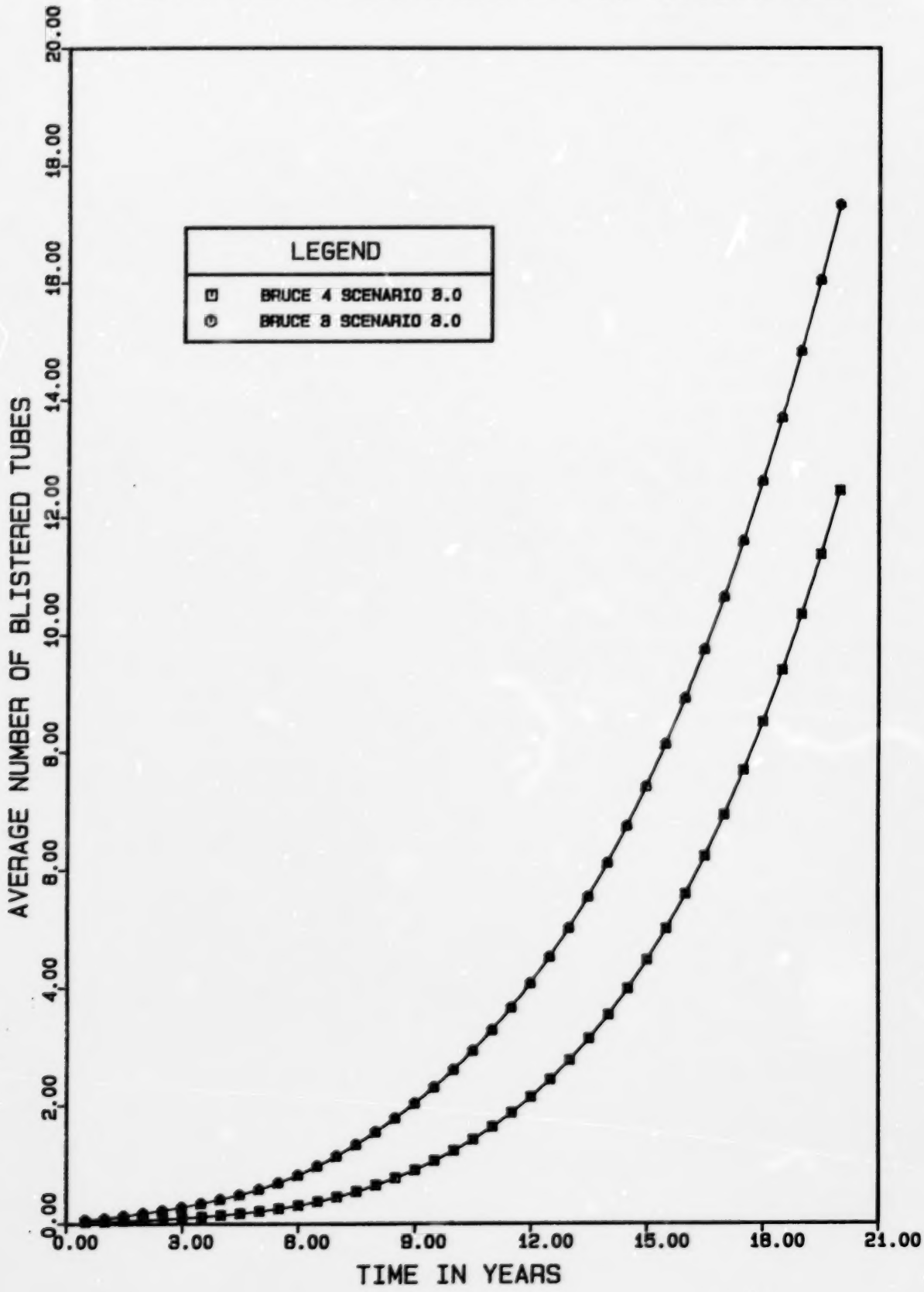

FIGURE 8

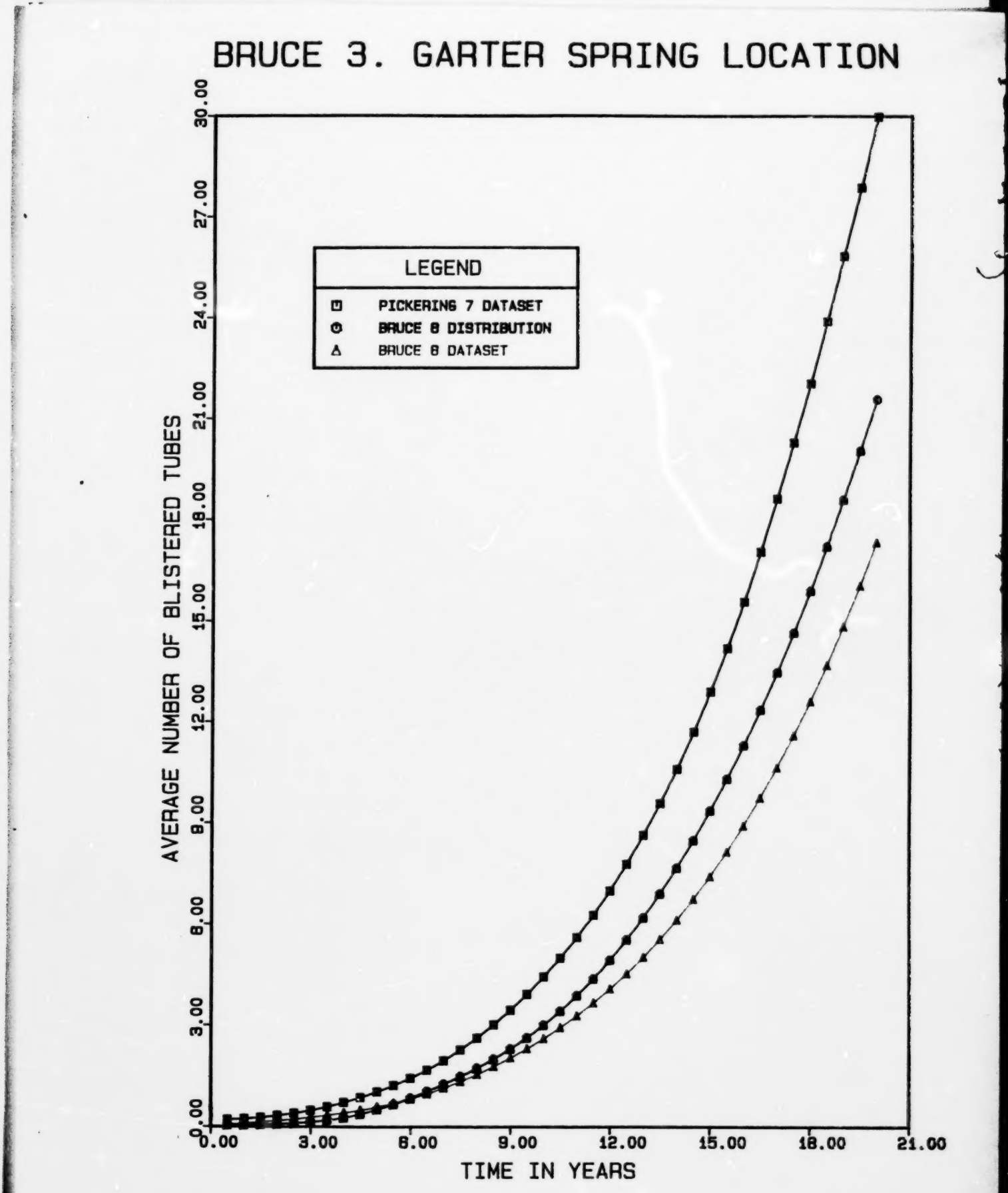
BRUCE 3. GARTER SPRING LOCATION
LEGEND
PICKERING 7 DATASET
BRUCE 8 DISTRIBUTION
BRUCE 8 DATASET
AVERAGE NUMBER OF BLISTERED TUBES
0.00
3.00
6.00
9.00
12.00
15.00
18.00
21.00
24.00
27.00
30.00
0.00
3.00
6.00
9.00
12.00
15.00
18.00
21.00
TIME IN YEARS

FIGURE 9

APPENDIX 1 - HYDROGEN THRESHOLD

The critical hydrogen content required for blister formation is dependent on three factors: 1) the temperature distribution in the tube in contact, 2) the terminal solid solubility related to precipitation of hydride in Zr-2.5 wt% Nb (TSSP) and 3) the heat of transport of hydrogen in Zr-2.5 wt% Nb.

The latter two factors are fundamental to the pressure tube material and cannot be expected to vary significantly from tube to tube. Unfortunately, these two factors cannot yet be confidently defined with precision although they are currently being measured experimentally. For this study, the estimate of TSSP derived from results of measurements on Zircaloy-2 and used in the blister growth calculations was employed/1/. The heat of transport was also taken to be that used in the blister growth calculations and is the result of measurements on other zirconium alloys (including annealed Zr-2.5 wt% Nb). It is important to note that there is good agreement between experimental blister growth results and the modeling carried out using the particular TSSP relationship and heat of transport data quoted above.

Establishment of the temperature distribution in a tube in contact is also complicated. The main complication here is the thermal boundary condition at the contact itself. It is the minimum temperature in the pressure tube at the contact relative to the local PHT temperature which is important for establishing the threshold levels. However, this minimum temperature is quite sensitive to the contact geometry, load, surface roughness, and the presence of oxide. The relationships between the PHT temperature and the contact temperature which were used for this study are shown in Figure A1. Of these scenarios chosen, the most conservative in terms of producing the lowest thresholds for blister growth (scenario 0) corresponds to having a 1 mm diameter contact spot carrying the load for a 25 mm length of contact with as-received tube surface conditions. This is clearly not the most conservative case which could be studied. The most optimistic scenario (scenario 1) corresponds to having a 20 μm air gap in the contact. Scenario 3 is considered to be the most realistic scenario taking reactor observations into account. It represents a case where there is a 20μm thick oxide film over a contact large enough that the heat flow is one dimensional in the center of the contact. The contact heat transfer coefficient used for this case is lower than the one measured experimentally on as-received tubes by about 15%.

The temperature profile of the PHT coolant along the tube depends upon the reactor and the particular zone of the reactor being considered. This information was obtained from available calculations performed by CNS using actual reactor conditions.

Figure A2 shows how the critical hydrogen threshold is derived when the PHT and contact temperatures are known. This figure incorporates the TSSP and heat of transport information noted above. As an example, the data for Bruce 3, scenario 3.0 are given for the central zone in Table 1.1. The table shows the PHT temperature, the contact temperature in the pressure tube, and the mean and standard deviation of the normal distribution used to describe the hydrogen threshold.

Reference

1. T.P. Byrne and M. Leger. Hydride Blister Growth Modeling - Progress Report 2. OHRD Report No 85-29-H. September 1985

TABLE 1.1

Threshold for Bruce 3 (Central Core) Scenario 3.0

Area	PHT °C	Contact Temperature	Hydrogen Threshold	Standard Deviation
1	255	203	18.2	3.0
2	265	211	21.0	3.6
3	278	220	24.0	4.25
4	288	227	26.0	4.85
5	297	234	28.1	5.5

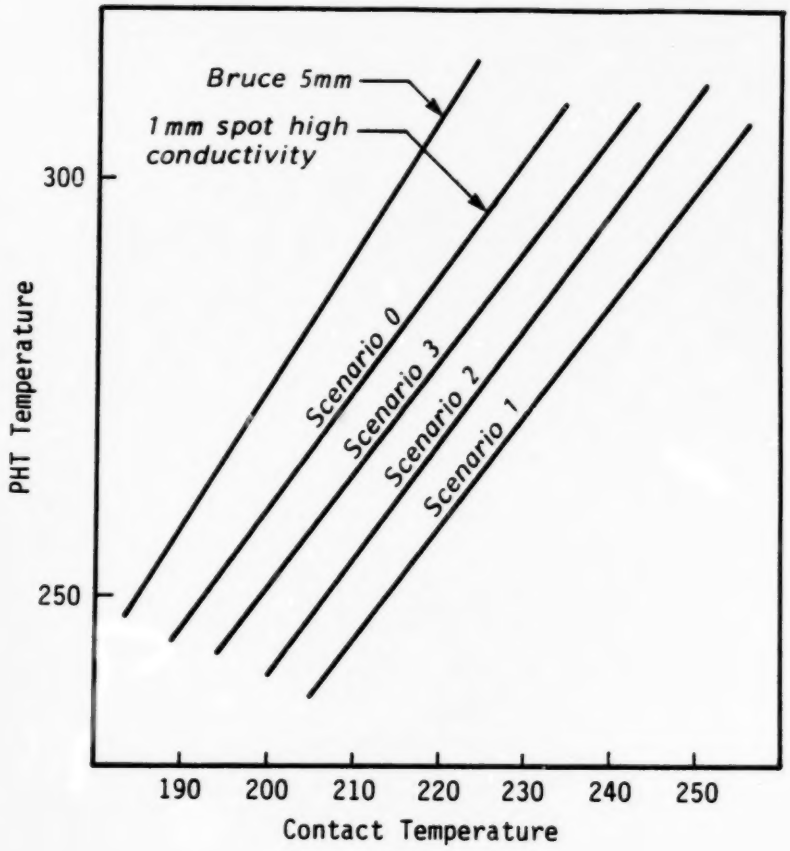

FIGURE A.1

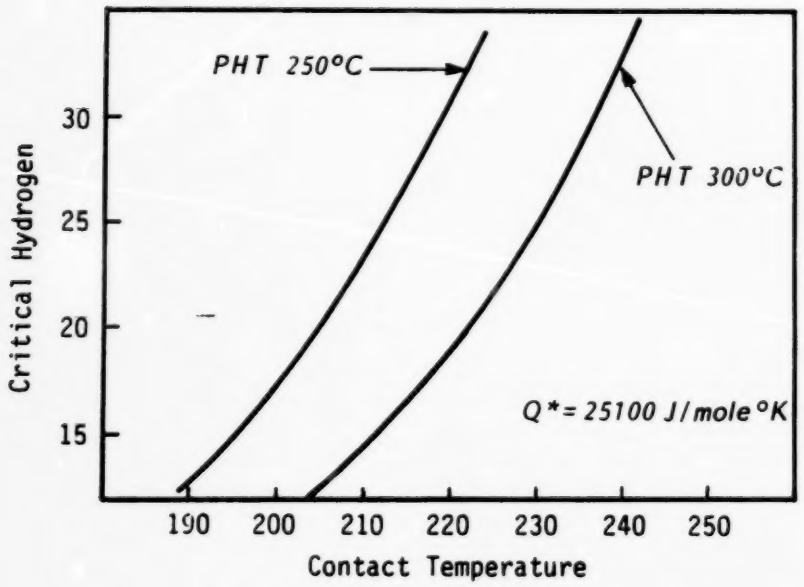

FIGURE A.2

APPENDIX 2 - INITIAL HYDROGEN CONTENT

The initial hydrogen distributions were based upon the hydrogen analyses of the first and last tube from each ingot. For the Bruce Unit 3 and 4 reactors, each lattice position was assigned two values corresponding to the measurements of the first and last tube from the same ingot as the tube at that particular lattice site. The effect of this assignment is to weight the measurements according to the number of tubes from each ingot in the reactor. The three reactor zones were treated independently. All these data were analyzed and tested versus different distributions. Plots were made (see for an example Bruce 3, Central Core data Figure A.3) which assisted in the choice of the most appropriate distribution, which was a Weibull distribution with lower cut-off 1 ppm below the lowest observed value. The values of the parameters of this distribution were determined by matching the first two moments of the distribution with the moments of the observations.

For Pickering Units 5 and 6, the distribution was determined from the measurements available for tubes installed in each reactor. In most cases, but not all, these were tubes from the front and back ends of ingots. Each measurements was equally weighted and no attempt was made to assign measurements to different reactor zones. The same basic procedure was followed to establish the representative distribution (Weibull with cut-off 1 ppm below the lowest observation and with matching moments).

The distributions used are given in Table 2.1.

TABLE 2.1

Initial Hydrogen Distributions

Reactor	Zone	Weibull			Mean	Standard Deviation
		Cut-off	σ	n		
Bruce 3	Central	4.0	5.94	1.55	9.34	3.52
Bruce 3	Intermediate	3.0	6.383	2.3	8.65	2.61
Bruce 3	Outer	3.0	6.254	2.2	8.54	2.66
Bruce 4	Central	3.0	6.079	2.4	8.39	2.39
Bruce 4	Intermediate	3.0	6.329	2.4	8.61	2.49
Bruce 4	Outer	4.0	4.379	1.7	7.91	2.37
Pickering 5	All	4.0	4.428	1.49	8.00	2.73
Pickering 6	All	4.0	4.636	1.78	8.13	2.40

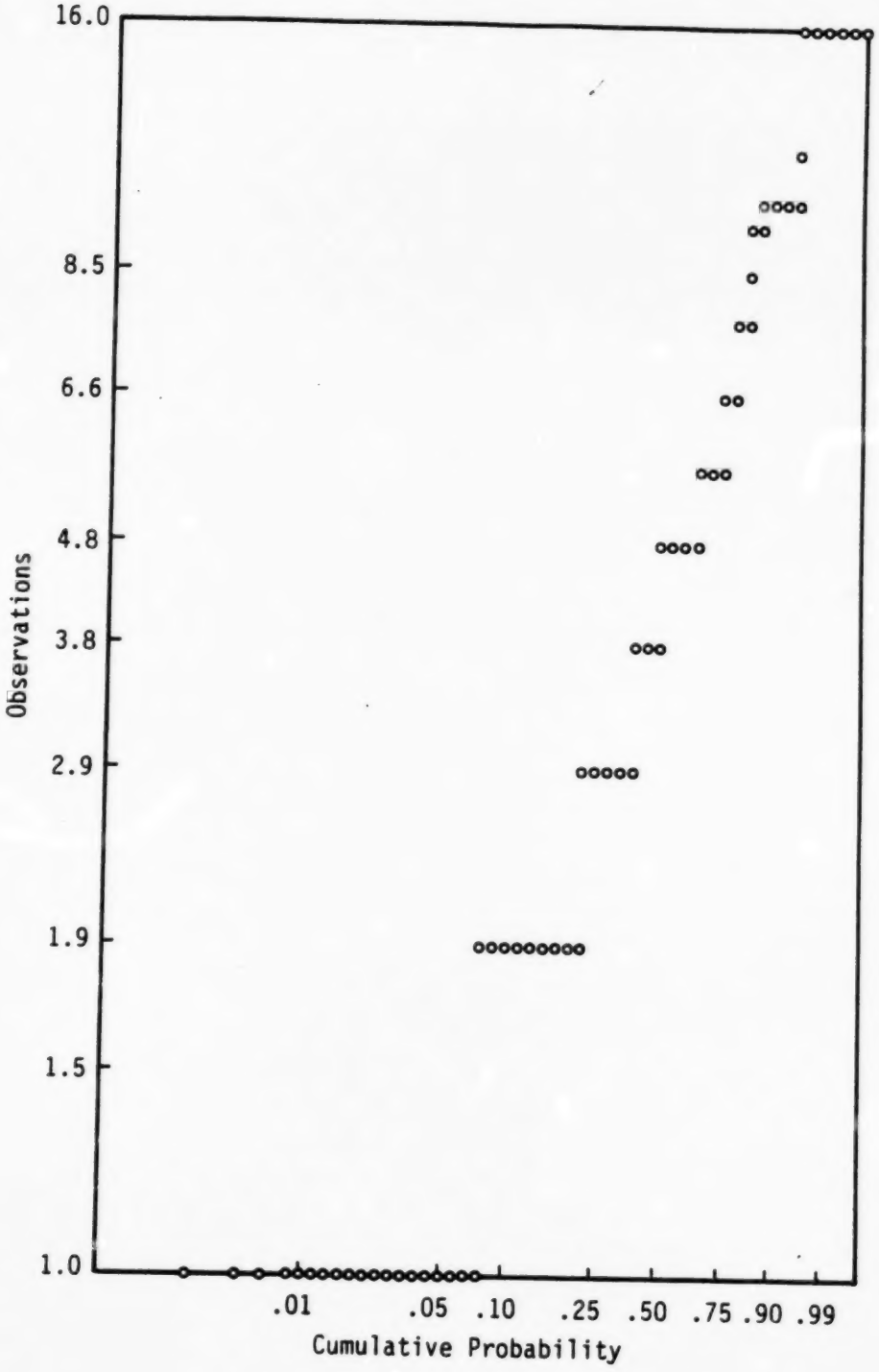

FIGURE A.3
PROBABILITY PLOT FOR WEIBULL DISTRIBUTION

APPENDIX 3 - HYDROGEN PICK-UP RATE

Few data were available for the estimation of this distribution. Nine measurements taken from Reference 1., were used to determine the parameters of a Weibull distribution (cut-off 0.0, σ = 0.347, n = 3.8) resulting in a mean hydrogen equivalent pick-up rate of 0.3136 ppm/EFPY and a standard deviation of 0.092 ppm/EFPY. These figures were determined assuming that the pick-up rate was constant for each tube over its whole life in reactor. The data are shown in Table 3.1 below.

The data finally reported in the SLAR assessment report/2/ are slightly different because only pickup in the zone of the tube where contact was possible was considered. A slightly lower average pick-up rate results. It should also be noted that for reasons of simplicity, the dependency of hydrogen pick-up rate on location along the pressure tube has been ignored.

TABLE 3.1

Pick-up Rate Data

Tube Designation	Average Deuterium PPM	Years	Equivalent Hydrogen Rate
P3F13	12.2	13.07	0.47
P4N16	9.1	11.86	0.38
P3J09	4.1	11.93	0.17
B2P12	4.0	7.86	0.25
B2J11	3.8	5.00	0.38
B1P13	2.5	4.29	0.29
B2X14	3.2	4.43	0.36
P3	1.0	1.86	0.27
P4	1.0	2.00	0.25

1. File Memorandum: Nuclear Systems Department, Design and Development - Generation Division, 907-SLAR-31100P (February 14, 1986), [Draft SLAR report]

2. Technical Assessment of Spacer Location and Repositioning, Nuclear Systems Department, Report No 86-066, April, 1986.

APPENDIX 4 - RELATIONSHIP BETWEEN SPAN LENGTH AND TIME TO CONTACT

The computer program requires a relationship between time to contact and span length. This relationship for pressure tubes in the central core was developed for both Bruce and Pickering reactors with four garter springs in the following way:

1. A distinction was made between areas along the pressure tube (inlet, outlet and inner = between garter springs).

2. It was ascertained that for the inlet and the outlet areas the differences between Bruce and Pickering were minimal.

3. For the inner areas, span length vs time to contact tables were tabulated for Bruce and Pickering GS from the data reported in the memoranda of C.J. Sullivan to C.O. Poidevin/1,2/. The data were smoothed and interpolation was done by means of cubic splines.

4. For the inlet and outlet areas of pressure tube in the central core, similar procedures were followed with the pooled data of Bruce and Pickering. Care has been taken to include those situations where the spring closest to the end is not pinched. The relevant distance then becomes the distance between the end and the next garter spring.

5. The relationships are shown in Figure A.4. Good agreement has been noted with other published data.

In the Sullivan memoranda only calculations regarding the central core are done. In order to deal with pressure tubes which are not in the central core, a scaling relationship was developed based on the work reported by V. Yu/3/. While this work deals with reactors with two garter springs (Pickering 3 and 4), it was possible to develop a relationship between the time to contact in the central zone and in the intermediate and outer zone respectively given a certain span length. A similar relationship is assumed to hold for four garter spring reactors and is shown in Figure A.5. Lastly, it should be noted that the time to contact is assumed to be a normal random variable with a standard deviation equal to one-fourth of the mean.

References

1. Memorandum G.J. Sullivan to C.O. Poidevin, "CDEPTH Predictions of P/T and C/T Time to Contact for Bruce NGS B, Unit 6" January 20, 1986, File 907-N-31020-255P.

2. Memorandum G.J. Sullivan to C.O. Poidevin, "CDEPTH Predictions of P/T and C/T Time to Contact for Pickering NGSB, Unit 7", February 3, 1986, File 907-N-31020-255P.

3. V.W. Yu, "Prediction of Pressure Tube to Calandria Tube Contact in PNGS A Units 3 and 4", Ontario Hydro Nuclear Systems Department, Report #843392, November 1984.

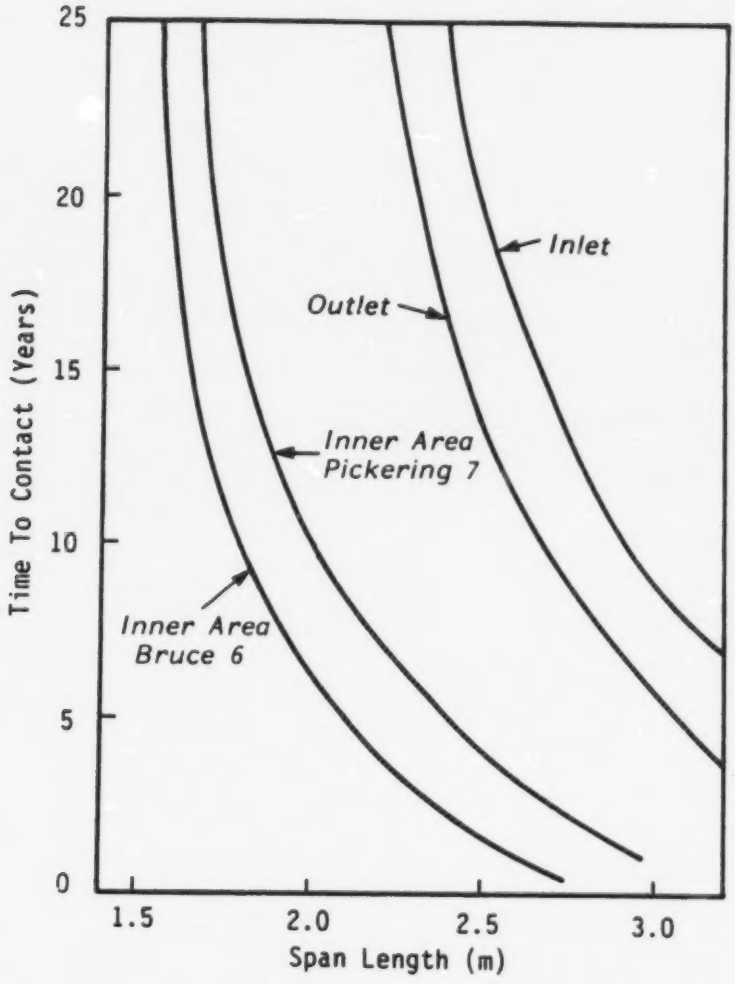

FIGURE A.4

SPAN LENGTH - TIME TO CONTACT RELATIONSHIP
FOR PRESSURE TUBES IN THE CENTRAL CORE

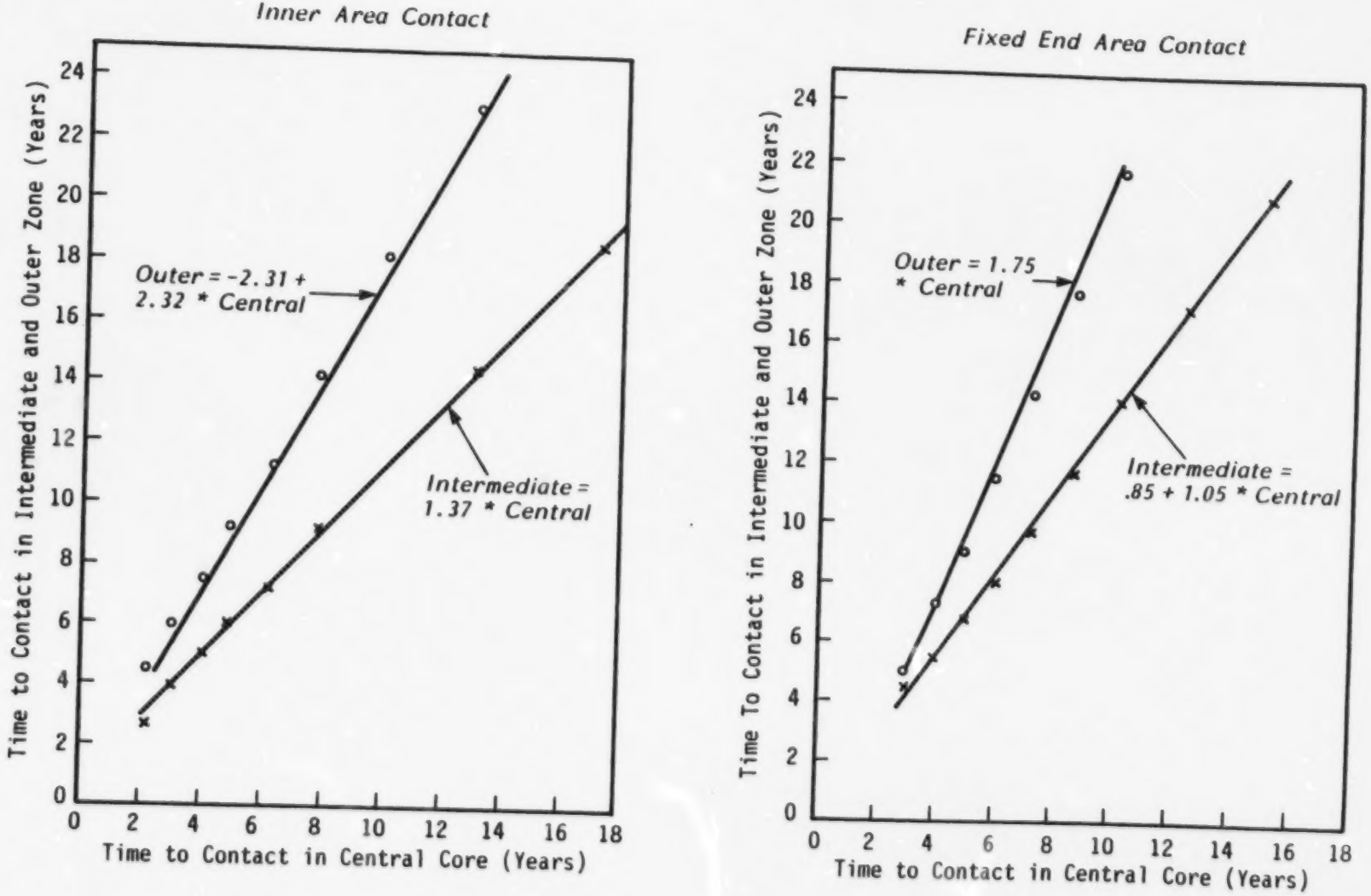
Inner Area Contact
Time to Contact in Intermediate and Outer Zone (Years)
Time to Contact in Central Core (Years)
Outer = -2.31 + 2.32 * Central
Intermediate = 1.37 * Central
Fixed End Area Contact
Time To Contact in Intermediate and Outer Zone (Years)
Time to Contact in Central Core (Years)
Outer = 1.75 * Central
Intermediate = .85 + 1.05 * Central

FIGURE A.5

RELATIONSHIP BETWEEN TIME TO CONTACT IN CENTRAL CORE AND TIME TO CONTACT IN INTERMEDIATE AND OUTER ZONES

APPENDIX 5 - GARTER SPRING LOCATIONS

Two major databases were available as information on garter spring location. Data were obtained for Bruce 6 and Pickering 7 for most pressure tubes (after hot conditioning but before repositioning). The Bruce 6 data was assumed to be representative of the distribution likely in Bruce units 3 and 4 while the P7 data was used for P5 and P6. The effects of using various garter spring distributions are discussed within the main body of the report. Clearly better data from the actual reactors would influence the final assessment.

The reactor was divided in three zones (outer, intermediate and central) and this proved to be felicitous. While an analysis of the whole Bruce 6 database indicated that the standard deviation increased with distance from the East end, the division in zones clearly demonstrates that the standard deviation is highly dependent on the zone of the reactor as shown in Table 5.1. Therefore, it indicates that a much better description of the garter spring location can be obtained by using this zoning approach which was not used in the work of J. Brimberg/1/. The other noteworthy observation is that the correlation between adjacent garter spring movements is also zone dependent and higher for the outer zones than for the central core. Therefore, the use of uncorrelated distributions for the outer zones is less legitimate than for the core.

Reference

1. J. Brimberg, Statistical Analysis for Pressure Tubes to Calandria Tubes Contact Times and Garter spring Loads for Pickering Units 5 to 8 and Bruce Units 5 to 7. Technical Document, AECL, Engineering Company 84-11-13.

TABLE 5.1
Bruce 6 Garter Spring Data
CENTRAL CORE

Referenced to the East Face

	MEAN (cm)	STANDARD DEVIATION (cm)
G1*	423.6	29.0
G2	525.3	31.1
G3	624.7	40.5
G4	721.9	48.1

CORRELATION TABLE**

	G1	G2	G3	G4
G1	1.00			
G2	0.28	1.00		
G3	0.03	0.09	1.00	
G4	-0.02	0.06	0.24	1.00

Referenced to Inlet End

	MEAN (cm)	STANDARD DEVIATION (cm)
GS1*	161.0	36.4
GS2	262.2	35.9
GS3	361.6	36.2
GS4	459.4	43.4

CORRELATION TABLE

	GS1	GS2	GS3	GS4
GS1	1.00			
GS2	0.25	1.00		
GS3	0.10	0.09	1.00	
GS4	0.00	0.01	0.26	1.00

*G1...G4 refer to garter springs numbered from the east face.
GS1...GS4 refer to garter springs numbered from the inlet end of the pressure tube.
** The values in the table indicate the degree of correlation between garter spring motions. A value of 1.00 indicates perfect correlation and 0.0 no correlation.

TABLE 5.1

Bruce 6 Garter Spring Data

INTERMEDIATE ZONE

Referenced to the East Face

	MEAN (cm)	STANDARD DEVIATION (cm)
G1	421.1	53.4
G2	522.7	60.1
G3	624.2	61.3
G4	718.1	68.1

CORRELATION TABLE

	G1	G2	G3	G4
G1	1.00			
G2	0.12	1.00		
G3	-0.11	0.20	1.00	
G4	0.05	0.09	0.36	1.00

Referenced to the Inlet End

	MEAN (cm)	STANDARD DEVIATION (cm)
GS1	160.4	60.6
GS2	260.9	57.0
GS3	362.3	64.4
GS4	457.4	62.9

CORRELATION TABLE

	GS1	GS2	GS3	GS4
GS1	1.00			
GS2	0.17	1.00		
GS3	-.10	0.20	1.00	
GS4	0.07	0.13	0.35	1.00

TABLE 5.1

Bruce 6 Garter Spring Data

OUTER ZONE

Referenced to the East Face

	MEAN (cm)	STANDARD DEVIATION (cm)
G1	397.2	101.5
G2	487.1	140.0
G3	563.1	162.4
G4	675.6	160.6

CORRELATION TABLE

	G1	G2	G3	G4
G1	1.00			
G2	0.55	1.00		
G3	0.44	0.77	1.00	
G4	0.32	0.53	0.63	1.00

Reference to the Inlet End

MEAN (cm)	STANDARD DEVIATION (cm)
184.0	149.2
296.9	163.8
372.9	153.0
462.4	135.5

CORRELATION TABLE

	GS1	GS2	GS3	GS4
GS1	1.00			
GS2	0.57	1.00		
GS3	0.47	0.78	1.00	
GS4	0.34	0.56	0.71	1.00

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